5th International Symposium on Hydraulic Structures Brisbane, Australia, 25-27 June 2014
Hydraulic Structures and Society: Engineering Challenges and Extremes
ISBN 9781742721156 - DOI: 10.14264/uql.2014.35

Spillway Rock Scour Experience and Analysis - the Australian Scene over the past Four Decades

E.F.R. Bollaert[1] and E.J. Lesleighter[2]
[1]Director, AquaVision Engineering
Ecublens,
SWITZERLAND
E-mail:admin@aquavision-eng.ch
[2]Director, Lesleighter Consulting Pty Ltd
Cooma, NSW 2630
AUSTRALIA
E-mail: lesleighter@yahoo.com

Abstract: *The challenge for spillway design over many decades has been to arrive at a design that can discharge floods of a wide-ranging magnitude without the scour of the material on and below which the spillway is founded. Typically, the material is rock; sometimes weak and poor quality rock for which various measures are applied to protect in the energy dissipation areas from scour that could lead to structural damage or failure. Sometimes the rock is strong and apparently of good quality. Nonetheless, in virtually all situations major scour has occurred. This is a world-wide experience. In Australia, those who design spillways have rightly considered the potential for scour, and rock scour. In many cases spillways have been constructed but have never been "put to the test". Our purpose is to go some way to lift the lid on what can really happen, making reference to recent major floods in Australia along the east coast. Our paper discusses numerous spillways, where over the past four decades, damage has been appreciable or extensive, the important hydraulic and geologic factors that comprise a vital part of dealing with the problems, and a few case studies where modern analysis procedures have been applied to explain the scour and quantify scour as a vital design component.*

Keywords: *spillways, energy dissipators, rock scour history, scour evaluation methods.*

1. INTRODUCTION

From 2010 the eastern areas of Australia have experienced flooding with several events being in the 1,000 year (Average Recurrence Interval (ARI)) category or larger; confirming the reality that such flood magnitudes are not just some number that we tend to think about, believing that it is 'never likely to occur', but they actually do happen. The recent experience has pressed home the realisation that not only do they happen on the dry Australian continent, but dam engineers need to be equipped to use methods to properly design for the energy dissipation pressures that they impose. It is notable when considering the occurrence of rock scour that there are two key realities. First, there are cases where ongoing appreciable scour occurs for floods of relatively high probability (low ARI values). Second, lower-probability floods (higher ARI values) are happening and need to be seriously embraced in the design of energy dissipation facilities - particularly when high-energy jets impact on natural rock masses.

In an effort to arrive at satisfactory designs for plunge pool energy dissipation, to avoid large-scale scour and deposition of scoured material out of the pools to become a hazard downstream, numerous empirical procedures have been applied over many years to estimate scour depths. These procedures are often based either on no information on the geology in the plunge pools or an inadequate way of dealing with the way rock masses break up and are washed away. It is not our purpose to describe or discuss the variability of the results from such procedures. Rather, we plan to discuss the two main computational methods which are being used by various designers for rock scour analysis. Both are regularly used on plunge pool scour problems worldwide - firstly, where possible, as a calibration with what has actually happened, and secondly to analyse the scour that is likely for future floods and how to safeguard structures against costly damage. We go on to discuss a number of Australian dams and spillways that have experienced major floods during the last four decades are discussed and described, together with details on the rock scour occurrences where available. Amongst this catalogue of scour cases, three or four are discussed in more detail, by applying various methods to analyse the scour.

2. SCOUR ANALYSIS PROCEDURES

2.1. Erodibility Index Procedure

The erodibility index procedure requires an assessment of a number of characteristics of the rock and the rock body. In summary, these are the:

- Rock strength (unconfined compressive strength (UCS)) and type
- Rock quality designation (RQD) and the number of joint sets
- Rock joint roughness number and a joint alteration number, which are determinants of the joint shear strength, and
- Orientation of the significant joints relative to the direction of the flow in the arriving jets.

Bringing the characteristics together to estimate an erodibility index, and comparison of this geomechanical value with an estimate of the stream power in the jet impacting the rock, a relationship is then used to determine whether erosion of the rock, either by dislodgment of rock units from the rock body or erosion of the actual rock surface, is likely or not. Several relationships in this category have been developed, amongst others by Moore et al. (1994), Annandale (1995) and Wibowo & Murphy (2004). The procedure states whether or not scour occurs, but is not able to provide temporal evolution of scour formation or details on the scour hole shape, which in turn limits the reliability of the estimate of the depth of scour.

2.2. Comprehensive Scour Model (Bollaert, 2004)

The Comprehensive Scour Model (CSM), developed by Bollaert (2004, 2012), estimates the ultimate depth of scour and the time evolution of scour in partially or totally fractured rock. The model is physics based and comprises a comprehensive assessment of the major geomechanical processes that are responsible for rock mass destruction by turbulent flow impingement:

- *hydrodynamic fracturing (CFM module)* of closed-end rock joints (that is, joints are not completely formed yet);
- *dynamic uplift (DI module) and/or peeling off (QSI module) of so-formed rock blocks* (that is, once the joint network is completely formed). This corresponds to processes 4, 5 and 6 in Figure 1.

The model consists of three modules: the falling jet, the plunge pool and the fractured rock. The modules for the falling jet and the plunge pool define the hydrodynamic loading that is exerted by the jet on the rock mass. The module for the rock mass has a twofold objective. First of all, it transforms the hydrodynamic loading at the water-rock interface into a critical stress inside the rock mass (for closed-end joints) or into a net uplift impulsion (for single rock blocks). Secondly, it defines the basic geomechanical characteristics of the rock mass, relevant for the determination of its resistance. More details on these modules can be found in Bollaert (2004, 2012).

As a function of future flood events, the model predicts the temporal evolution of scour formation and, when correctly calibrated, the temporal evolution of the general 2D shape of the scour hole. It is also able to estimate the potential beneficial influence of rock anchors in mitigating scour formation.

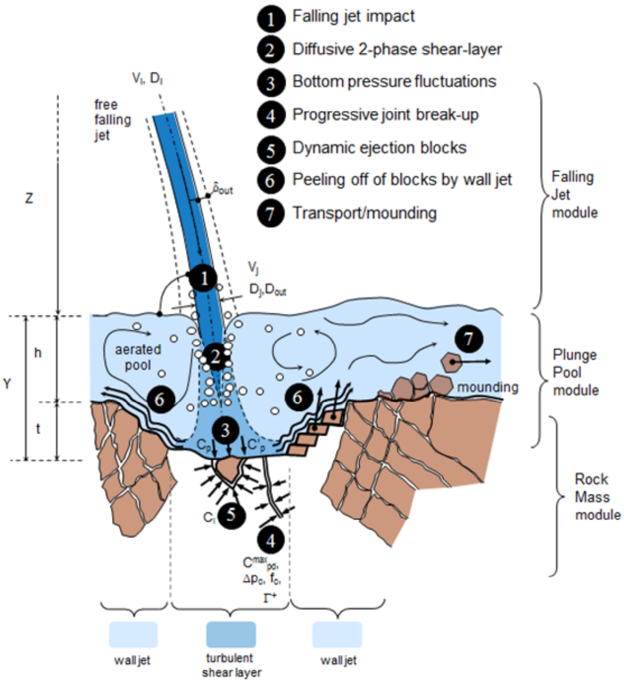

Figure 1. Main physical processes used for numerical computation of rock scour (CSM)

3. CATALOGUE OF MAJOR FLOODS AND SCOUR CASES IN AUSTRALIA

3.1. Awoonga Dam

Awoonga Dam is a concrete-faced rockfill dam on the Boyne River, Queensland. It is 55 m tall, the spillway crest level is EL 40 and the crest length 111 m. It has a saddle dam with a top elevation of EL47.9 m. In January 2013 the Awoonga Dam spillway experienced an overtopping head of 8.3 m (reservoir level EL 48.3 m). Hydrologic data indicate that the AEP 1 in 1,000 and 1 in 2,000 peak levels are approximately EL 47.8 m and EL 48.4 m, respectively. The 2013 flood had an estimated AEP of 1 in 1,800. A saddle dam was overtopped by around 0.4 m during the flood, fortunately with limited damage. The spillway, shown in flood in Figure 2, has a chute which slopes to the end where chute blocks are used to provide vertical spread to the jet. Thereafter, the flow passes over an excavated tailwater channel. It was found that rock in the spillway channel below the apron scoured over a distance of 50 m downstream with a maximum depth of approximately 3 m, but typically less than 2 m. The case is cited to illustrate that a flood as rare as the 1,800 year period cannot be dismissed as so unlikely that the structure is not called to account for discharges of such magnitude.

Figure 2. Views of Awoonga spillway in January 2013 flood (Photos: Gladstone Area Water Board)

3.2. Borumba Dam

Borumba Dam was built on Yabba Creek a tributary of the Mary River in Queensland in the early 1960s. It is a concrete-faced earth and rockfill embankment with a spillway in the left abutment. The spillway has a 101 m long ogee crest with flow into a partly side-channel configuration. The chute is super-elevated and follows a curved alignment to the discharge point, where the discharges flow into a plunge zone bounded by natural material, largely rock which has been described as "highly fractured slate, phyllite, quartzite, breccia and greenstone" (SunWater report, 2001). The rock was of low strength with defect spacing based on one drill hole of around 30 mm and the RQD value essentially zero. In February 1999, a flood reported to have an AEP of approximately 1 in 100, with a peak discharge of approximately 1,800 m^3/s, caused deep scour in the rock below the end of the concrete chute, down to around EL 98, 9 metres below the level of the end of the chute (SunWater, 2001). That flood produced a reservoir level of EL 141 m AHD, approximately 34 m above the level of the end of the chute. Figure 3a is a view of the spillway looking up the super-elevated chute. Figure 3b is a view of the scour hole below and near the chute following the 1999 flood. Figure 4 shows the extent of scour farther downstream from the end of the chute, revealing a second downstream scour hole. The end of the chute is visible in the top right of the photograph.

The experiences at Borumba Dam highlight the capacity of discharges with relatively low head (less than 40 m from reservoir to tailwater levels), to create deep scour in the presence of concentrated flows and intense eddy action. The complex planform geometry causes a concentration of flow to the right hand side due to the curved spillway chute geometry. The character of the erosion and the likely flow pattern indicates a strong back flow below the jet exiting the chute, a mechanism which is addressed in the Quasi-Steady Impulsion (QSI) module of Bollaert's Comprehensive Scour Model.

Figure 3. a) Borumba Dam spillway; b) Rock scour below spillway from 1999 flood (SEQWater photos)

Figure 4. Wide view of the scour below the spillway (SEQWater photograph)

3.3. Copeton Dam

Copeton Dam, a 113 m tall dam, was built on Gwydir River, New South Wales in 1976. It has a gate-controlled ogee-crested spillway with discharge across a short concrete chute, and then onto a gently-sloped excavated rock surface. It has been reported that "*unexpected erosion of hard, sound, unweathered granite in the unlined spillway discharge channel was caused by rock failure under high in-situ compressive stress. This type of erosion due to high in-situ stress has not been reported elsewhere in the world*" (Woodward et al, 1980). The spillway has experienced deep scour of the rock during a number of floods – all of relatively low ARI. The unlined discharge channel was located in coarse-grained granite intruded by some dykes of fine-grained granite. Carter (1979) reported that "*two relatively minor discharges in 1976 scoured some 100,000 m^3 of mainly fresh granite from a well-defined gully in the centre of the discharge channel*." The flood discharges were reported to be 200 m^3/s (January 1976) and 460 m^3/s (February 1976 - 3%, only, of the design discharge of 14,800 m^3/s), both discharging for nine days. In places the scour was 25 m to 30 m deep. Information on observed scour is sourced from Woodward, by permission (1985, 1992). Figure 5a shows the erosion chasm. Following the floods, slabs of granite heaved from the channel floor and rock-popping could be heard for several weeks afterwards. The development of wide cracks in the granite is illustrated in Figure 5b.

Figure 5. a) Deep scour in Copeton spillway channel; b) Extensive cracking as rock "popped" after the scour occurred (photos courtesy Dr Richard Woodward, geologist)

3.4. Julius Dam

Julius Dam is a 38 m high concrete barrel-arch buttress dam on the Leichhardt River in north-western Queensland. It has an overfall spillway with flow over a crest above 12 of the barrels at EL 223.54. The spillway section is 219.46 m long. The flow over the spillway section free falls onto a concrete "dissipater pad" beyond which the river bed is composed of hard rock. Following flood discharges over the spillway in 1997, with a maximum discharge of 4,900 m^3/s, remedial work downstream of the dissipater pad and along the retaining wall section on each side of the spillway was required. Figure 6a is a general view of the dam. The geology information describes the dam site as being located in quartzite and slate. Figure 6b shows the highly fragmented quartzite just downstream of the dissipater pad. Potential for further damaging rock scour was considered using both the Annandale erodibility index procedure (Annandale, 1995), and the Comprehensive Scour Model of Bollaert (2004, 2012). The work was published (Lesleighter & Bollaert, 2008) and is summarised in here.

The erodibility index procedure was applied for two key discharges – the AEP 1 in 10,000 and the Probable Maximum Precipitation Design Flood (PMPDF) discharge. On the basis of the geologic assessment, the various components of the erodibility index for its estimation were derived. Some of the key values were assessed - a UCS between 70 and 150, an RQD between 10 and 50, and 4 joint sets. With certain reservations about aspects of erodibility that the procedure tends to miss, the results indicated a geology that would be under major stress in the event of the extreme flooding that is now considered a legitimate likelihood in the present hydrologic context.

Figure 6. a) Overview of dam spillway; b) Fragmented quartzite downstream of dissipator pad

For application of the CSM procedures, first the hydrodynamics of the overtopping jets were determined. Second, scour formation was computed as a function of the time duration of the flood scenarios in question. The related computational assumptions included:

- Consideration of a hydrograph for the flood scenarios that overtops the crest for about 1-2 days
- Direct jet impact onto the rock bed, i.e. the jet impacts a rock bed situated above the TW level, and scour forms a local hole with a progressively increasing water depth that diffuses the jet.
- The jet directly impacts on the rock bed, or, for indirect jet impact onto the rock bed, the jet plunges and diffuses into the downstream tailwater before impacting the rock bed, where it sets up hydrodynamic pressures on the rock bed and transmitting them into the rock joints.

For the AEP 1 in 10,000, scour formation was found to be strongly limited by the assumption of local pool formation, which quickly dissipates most jet energy. However, overflow of the abutment sections of the dam would not have the benefit of a water body and a scour hole would form. The PMPDF scenario generates a compact jet with a core thickness of several metres upon impact, with the result that the scour formation is more significant. Figure 7 provides the evolution of scour based on the duration of the flow conditions.

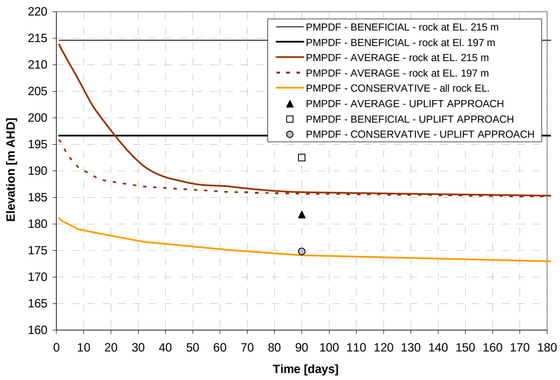

Figure 7. Time evolution of scour computed by the Comprehensive Scour Model for PMPDF (Lesleighter & Bollaert, 2008)

From the time aspect, considered in the CSM procedures, it was determined that the scour would form rather slowly and be quite limited within one single event. For conservative parametric assumptions, however, scour forms quasi-instantaneously down to a depth of around 35 m, followed by a much slower progression with time. In this case, the assumptions consider the rock mass in a very advanced state of break-up of the joints; the rock mass being regarded as an ensemble of almost distinct rock blocks that can be uplifted and swept away. In other words, the dynamic block uplift approach becomes more relevant than a fracture mechanics approach. The results of the rock block uplift computations confirm the above results, with a quasi-instantaneous scour formation by rock block uplift down to 40 m below the dissipator pad level, depending on the parametric assumptions. The results are independent of the initial rock bed level considered during the computations.

3.5. Burdekin Falls Dam

The Burdekin Falls Dam is a concrete gravity dam with a 504 m long overflow spillway. A general view is shown in Figure 8a. The crest level is EL 154 and the average apron level is EL 121.The peak-discharge overflow experience between the years 1990 and 2000 reveal a number of floods of appreciable magnitude. A large flood occurred in February 1991 when the head on the spillway was up to 6.85 m and the estimated discharge 19,196 m^3/s (unit discharge q, 38 m^2/s). In February 2009, another flood with a spillway head of 6.65 m occurred. The flood discharge is shown in Figure 8a. The rock had been anchored for some distance downstream of the apron. However, delamination of the rock had been experienced with the result that anchors were left exposed, as shown in Figure 8b. The rock in general is very hard with a large unconfined compressive strength (UCS), reportedly up to 380 MPa. There are sub-horizontal joints at variable spacing over virtually the whole rock body downstream of the dam. As well, there are a number of near-vertical joint sets (at least three) throughout. Investigations at different times have revealed that the rock body is highly stressed in the horizontal plane and this has been observed to cause “popping” as exposed surfaces delaminate.

Figure 8. a) Burdekin Falls spillway 2009 flood with 6.65 m head; b) Exposed anchors following removal of top layers of rock

A number of relevant investigations have been made to address hydraulic and geologic issues relating to the question of more erosion. Part of these investigations relate to the work performed by Otto (1989 – personal communication), who studied the quasi-steady uplift of protruding rock plates due to jet impingement just upstream of the plate side face and based on the formation of suction pressures along the upper face of the plates. About 20 years after this work, and based on several other similar works, this physical principle of peeling off of flat-shaped rock bodies due to quasi-steady pressure differentials over and under the bodies has been developed by Bollaert (2012) in the QSI module of the Comprehensive Scour Model. This QSI module is able to express the shape of the scour hole during scour formation, which is of particular relevance in case of scour regression towards the dam toe. Also, the module is able to estimate the potential beneficial influence of added rock anchors on scour development with time. This might be of particular interest to perform design and numerical optimisation of planned scour mitigation measures, such as might be imagined on Burdekin Falls Dam. Figure 9 is a schematic of a potential scour shape following a (future) significant flood.

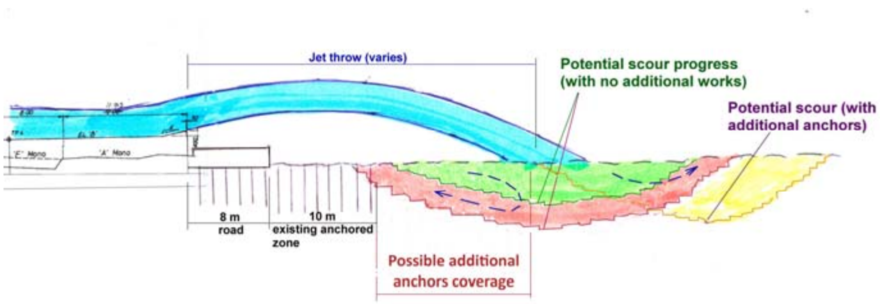

Figure 9. Possible potential scour profiles at Burdekin following a significant flood event

The schematic includes a conceptual layout of possible additional anchoring to limit the potential scour depth and regression. Without any detailed local geologic analysis, it *a priori* seems to indicate the need for scour mitigation works, as indicated, to prevent back-cutting scour. Whether or not additional anchors would solve the problem, and how much and deep the anchors should be, are complex design issues where the Comprehensive Scour Model is typically of significant value to the design engineer.

3.6. Boondooma Dam

Boondooma Dam is a 570m long, 63m high concrete faced rockfill embankment dam on the Boyne River, Queensland. It has an uncontrolled unlined spillway excavated in rock on the left abutment. The unlined chute of the spillway channel has a concrete erosion control structure at the downstream end, from which flow drops over into a plunge pool. Figure 10 shows the crest structure and the unlined chute down to the erosion control structure.

Figure 10. Boondooma Dam spillway crest and unlined spillway channel

Significant scour below the erosion control structure was observed after a period of low to moderate discharge in the Spillway during January 2011. The peak discharge had an AEP of approximately 1 in 30 (1,500 m^3/s). In January 2013 another flood peaked at about 3 500 m^3/s and was assessed as being roughly the AEP 1 in 200 flood. The scour in the plunge zone below the erosion control structure was again considerable. The extent of the main scour is shown in Figure 11 as viewed from the erosion control structure. The plunge pool increased appreciably in its pool surface area. One aspect of the scour is the occurrence of backflow below the main jet which led to some regression of the rock face below the erosion control structure.

Figure 11. Boondooma spillway plunge pool below erosion control structure

3.7. Wivenhoe Dam

In January 2011 major flooding was experienced across a large part of Southern Queensland. The flood discharges through the Wivenhoe Dam spillway caused extensive erosion of the rock in the plunge pool. The dam has a gated ski-jump spillway discharging into a pre-excavated unlined plunge pool and outlet channel. The spillway has five radial gates each 12 m wide and 16 m high. The ogee crest is at EL 57.0 m AHD, the flip bucket lip at EL 45.0 m AHD, and the Full Supply Level (FSL) at EL 67.0 m AHD.

While not an issue in relation to the spillway structure's security, the rock erosion experience was dramatic for a number of reasons. From the sheer volume of rock that was lifted up and out of the plunge pool, the occurrence stands as a demonstration of what can happen, and suggests the type of awareness that spillway design needs to accommodate for energy dissipation facilities in unlined spillway plunge pool. The discharges over several days resulted in a pile of huge rock blocks downstream of the plunge pool. Figure 12a shows the rock mound following the flood and Figure 12b the longitudinal scour profile measured along the centreline – with distance from the bucket lip (red curve). Details of the extent of erosion under head conditions that can be classed as moderate only when compared with many taller dams, have been described in a number of publications (Lesleighter et al, 2013, and Stratford et al, 2013).

Application of the Comprehensive Scour Model to the 2011 event is shown in Figure 12b (dotted black curve). The model is capable to reconstitute the observed scour, which clears the way for further scour predictions applicable, for example, for more extreme events.

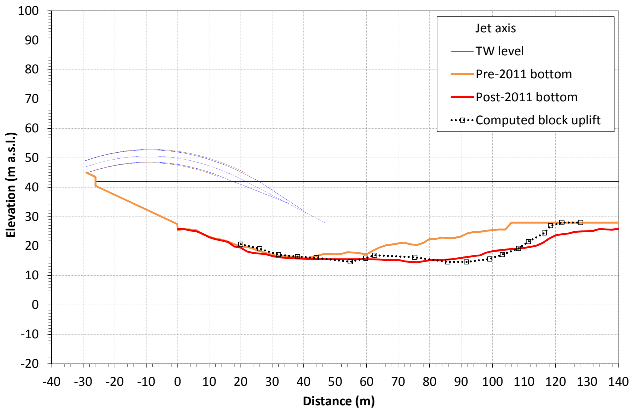

Figure 12. a) Rock mound in spillway channel; b) Numerically computed scour profile following the 2011 flood at Wivenhoe Dam

4. DISCUSSION OF SCOUR CASES

It is no real surprise that the last 4 decades of flood events have generated significant scour on a large number of spillways and plunge pools throughout Australia.

Interestingly, even though floods of significance have occurred earlier and have been cited earlier, a lot of extreme flood events occurred during the last 10-15 years, with peak floods during the years 1997 (Julius), 2009 (Burdekin), 2011 (Wivenhoe), 2013 (Awoonga), 2013 (Boondooma) among others. These have caused significant damage on spillways and plunge pools that, for most of them, had never or almost never been functioning at high specific discharges before. As such, their efficiency in preventing scour from occurring was unknown before the event.

This recent trend of increase of specific discharges on most spillways and the related scour problems that start to arise are certainly not specific to Australia, the phenomenon is being observed worldwide.

Nevertheless, it has allowed during the last decade the generation of public as well as professional awareness of potential scour problems on dams in Australia.

Part of this awareness is being expressed by increasing professional interest into the latest technological developments related to scour prediction and mitigation, such as for example the Comprehensive Scour Model. In this sense, the authors of the present paper are currently working on a certain number of scour cases where the original designs of the appurtenant structures are being tested for their efficacy in mitigating potential scour during future extreme events.

5. ACKNOWLEDGMENTS

The authors express their sincere appreciation to several organisations that have permitted presentation of details of their dams and information that they supplied in our paper. They include Dr Richard Woodward, Gladstone Area Water Board, SEQWater, and SunWater Limited.

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